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Analysis of air pollutant distribution at the incinerator hazardous waste treatment facility in Nambo Village, Regency of Bogor

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ABSTRACT

The population of Indonesia continues to grow every year, resulting in an increasing number of industries to meet the needs of daily life. The growth in the number of industries reflects the progress of national economic development. However, industrial activities, in addition to generating positive impacts on economic growth, also produce negative impacts on the environment. The generation of Hazardous and Toxic Waste (B3 waste) is one of the negative consequences of industrial activities which, if not properly managed, can pose serious risks to the environment, human health, and the sustainability of the industrial activities themselves. One of the available options for managing B3 waste is treatment using incinerator technology. This study was conducted with the objective of determining and analyzing the concentrations of air pollutants in both emissions and ambient air, as well as the spatial distribution of air pollutants, specifically SO_2, NO_2, and Total Suspended Particulate (TSP), released from the incinerator chimney that have the potential to pollute the environment surrounding the company's operational area, by comparing the results with baseline data used during the preparation of the Environmental Impact Assessment (AMDAL). This study employed a quantitative analytical approach using the concepts of classification, calculation, measurement, and causal relationship analysis to address the research questions. Meteorological data were utilized, including wind rose analysis, atmospheric stability classification, determination of receptor points, and analysis of wind speed profiles, which were processed using WRPlot software. Furthermore, dispersion patterns were interpreted and visualized using Surfer software to identify pollutant dispersion characteristics. The results of the study indicate that the distribution of SO_2, NO_2, and TSP pollutants does not cause pollution in the surrounding environment, and the measured concentrations remain below the government-established ambient air quality standards and are consistent with the analysis data used during the AMDAL preparation. The scope of the measurements was limited to the distribution of air pollutants around the company's operational area in accordance with the AMDAL document, and the measured parameters were key air quality indicators referring to Government Regulation No. 22 of 2021, Appendix VII, namely SO_2, NO_2, and TSP.

Keywords: *Air pollution distribution, AMDAL, dispersion model, hazardous waste, incinerator*

INTRODUCTION

The continuously growing population of Indonesia each year encourages an increase in the number of industries to meet the basic needs of life, which has become an unavoidable requirement. This increase in industrial activity reflects the progress of national economic development. However, despite its positive contribution to economic growth, industrial development also has negative impacts on environmental quality. To mitigate existing environmental challenges, Monk & Priatna (2022) argue that developing countries like Indonesia need to develop environmental security and resilience to maintain environmental quality.

In response to these environmental challenges, the Government of Indonesia has established several legal instruments to regulate environmental protection and management. Law Number 32 of 2009 concerning Environmental Protection and Management serves as a fundamental regulatory framework to oversee environmental governance. This law stipulates the obligations of business entities and industrial operators to manage waste generated from their activities, as well as provisions related to sanctions and fines for non-compliance. Furthermore, Government Regulation No. 22 of 2021 concerning the Implementation of Environmental Protection and Management specifically regulates the management of hazardous and toxic waste (B3) (GoI, 2021a; GoI, 2021b). Hazardous waste (B3) is defined as waste that possesses hazardous and toxic properties, where B3 refers to substances, energy, and/or other components that, due to their nature, concentration, and/or quantity, can directly or indirectly pollute and/or damage the environment and pose risks to environmental quality, human health, and the survival of humans and other living organisms (Ghorani-Azam et al., 2016; KLHK, 2021).

Improper hazardous waste management that does not comply with regulatory standards has the potential to cause significant environmental degradation and adverse impacts on humans and other living organisms (BPDLH, 1996). Therefore, it is essential to maintain a balance between fulfilling human needs, supporting industrial growth, and ensuring environmental sustainability.

Achieving this balance is necessary to create a harmonious relationship between humans, the environment, and other living organisms (Djuned, 2016).

Hazardous waste management encompasses a series of activities, including waste reduction, storage, transportation, collection, utilization, processing, destruction, and final disposal through landfill. In this context, Indonesia has developed an integrated hazardous waste management facility that operates all stages of hazardous waste management as outlined above. This facility is located in Nambo Village, Klapanunggal District, Bogor Regency, West Java Province, and has been operating since 1995. One of the hazardous waste treatment technologies implemented at this facility is thermal treatment using an incinerator system (Gusdini et al., 2023).

Despite its effectiveness in reducing hazardous waste volume, incineration generates pollutant emissions that have the potential to cause environmental pollution. Various types of hazardous waste processed in incinerators, whether in solid, liquid, or gaseous form, can produce air pollutants that may pose risks to the environment, surrounding communities, and facility employees. These pollutants are emitted through the incinerator chimney and subsequently disperse into the surrounding atmosphere. Therefore, assessing the dispersion of air pollutants from the emission source is necessary to evaluate their potential environmental impacts. One widely used approach for this purpose is the application of air pollutant dispersion models (Rahmadhani, 2017). The Gaussian plume model is commonly applied to examine the relationship between input parameters and resulting pollutant concentrations (Sabin et al., 2000). This model represents a mathematical description of air pollution dispersion, particularly for point sources such as chimneys, where contaminants are assumed to disperse following a Gaussian or normal distribution. The impacts of non-reactive pollutants originating from point or line sources are frequently estimated using Gaussian models (Arya, 1999). Previous studies have demonstrated the applicability of Gaussian models in pollutant dispersion analysis. For example, Suryani & Gunawan (2010) developed a model of SO_2 dispersion from the cement plant chimney of PT Semen Tonasa in Tuban (Sugiharto, 2015).

The dispersion behavior of pollutants released into the atmosphere is strongly influenced by atmospheric dynamics, including air temperature, turbulence, wind speed and direction, and atmospheric stability. Consequently, effective and representative air quality monitoring is required to accurately characterize ambient air pollution around emission sources (USEPA, 2021). The magnitude and spatial distribution of pollutant concentrations depend largely on prevailing meteorological conditions at the time of emission and measurement (Damara et al., 2017).

The Company has prepared an Environmental Impact Assessment (AMDAL) document, which was initially developed in 1993 and has been periodically updated to accommodate changes and additions to operational facilities in 2008, 2014, and 2018. In addition to the AMDAL, the Company has implemented the ISO 14001:2015 Environmental Management System (SML), which provides a structured framework for managing environmental aspects and impacts. Through the implementation of the SML, several environmental risks associated with hazardous waste processing activities have been identified. In this study, baseline data and predicted pollutant dispersion presented in the AMDAL document are compared with current field measurements to evaluate consistency between predicted and actual environmental conditions and to assess the effectiveness of existing environmental management practices.

METHODS

Research Location

The research was conducted at B3 waste processing facility which located in Nambo Village and Bantarjati Village, Regency of Bogor, during the period of April 2024 to February 2025, as shown in Figure 1.

Figure 1. Research location at B3 waste processing facility in Nambo and Bantarjati Villages, Regency of Bogor, and the map of monitoring points.

The detailed information regarding the location of the monitoring points is shown in Table 1.

Table 1. Parameter, weight & score of landslide susceptibility in Babakan Madang District.

Monitoring Point	Location	Coordinate	
		LS	BT
AAM-1	PCBs Treatment Area	06^{0}28' 19,14"	105^{0}55' 19,77"
AAM-2	Nambo Soccer Field Area	06^{0}28' 12,38"	105^{0}55' 28,29"
AAM-3	Side Basin - 6 Area	06^{0}28' 16,98"	105^{0}55' 25,40"
AAM-4	Puskesmas Nambop Area	06^{0}28' 02,67"	105^{0}55' 28,37"
AAM-5	Perimeter Barat Landfill Area	06^{0}28' 06,41"	105^{0}55' 44,38"

Tools and Materials

The tools and materials utilized in this study consisted of air sampling instruments and laboratory analytical equipment for air quality assessment, Surfer and WRPlot software applications for data processing and visualization, and a computer or laptop to support data analysis and modeling activities.

Research Design and Methodology

This study applied a quantitative research approach based on secondary data analysis, field observation, and a comprehensive literature review. The methodology was designed to evaluate air pollutant emissions from an incinerator facility and their dispersion in the surrounding environment. Data collected in this study included information on the type of incinerator, fuel characteristics, and types of hazardous waste processed. Emission concentration calculations were conducted for selected air pollutant parameters released from the incinerator chimney. In addition, ambient air quality around the operational area was analyzed to assess potential environmental impacts. These calculations were further supported by local climatic and meteorological data to determine spatial patterns of air pollutant dispersion.

Data Collection

Data collection was carried out through a systematic review of scientific journals, books, and other relevant publications related to air pollutant dispersion and atmospheric modeling. Secondary data used in this study were obtained from the following sources:

1. Meteorological data were collected from the Meteorology, Climatology, and Geophysics Agency (BMKG), including records of weather conditions at the study location over the previous two years. Spatial and regional map data were obtained from Google Earth to support spatial analysis and visualization.
2. Ambient air quality data included measured concentrations of sulfur dioxide (SO_2), carbon monoxide (CO), nitrogen dioxide (NO_2), ozone (O_3), Total Suspended Particulate (TSP; <100 µm), particulate matter less than 10 µm (PM_{10}), particulate matter less than 2.5 µm ($PM_{2.5}$), and lead (Pb), as reported in relevant monitoring data and previous studies (Ashrafi et al., 2018).

Data Analysis and Processing

Laboratory analysis results and meteorological data were processed and analyzed through several sequential steps. Meteorological data analysis focused on key atmospheric parameters, including wind rose characteristics, atmospheric stability classification, determination of receptor points, and wind speed profile analysis. These parameters were analyzed using WRPlot software to describe prevailing atmospheric conditions influencing pollutant dispersion.

Subsequently, calculated air pollutant concentration data were processed using Surfer software to generate spatial dispersion maps. These maps were used to visualize and interpret the dispersion patterns of air pollutants emitted from the incinerator chimney within the study area.

RESULT AND DISCUSSION

Type of Incinerator, Fuel and Type of B3 Waste

The company operates a rotary kiln incinerator unit with a vertical stoker configuration that functions as a continuous system capable of operating for 24 hours. Diesel fuel is used only during the initial ignition phase, when no waste is fed into the incinerator (0% loading). After the start-up phase, the combustion process is sustained by the waste materials entering the incinerator, which possess sufficient calorific value to maintain the required temperature within the combustion chamber. The calorific value of mixed waste ranges from 3,395 to 4,245 cal g^{-1}, while oil-based waste exhibits higher calorific values, ranging from 9,638 to 10,536 cal g^{-1}. Furthermore, the vertical stoker-type incinerator enhances combustion efficiency, particularly for waste types that are capable of self-sustained combustion.

These findings indicate that the high calorific value of the processed waste supports stable and efficient incinerator operation with minimal auxiliary fuel consumption, thereby contributing to improved combustion efficiency and energy utilization. Minimizing energy use, especially from fossil fuels, significantly contributes to climate change mitigation efforts (Priatna & Monk, 2023; Priatna & Khan, 2024).

The various types of hazardous waste processed in the Incinerator unit presented in Table 2.

Table 2. Types of B3 waste processed in incinerator.

No	Name of Waste	Physical	Industry
1	Used rags	Solid	Automotive, Chemical
2	Effluent	Liquid	Company Internal Activity
3	Medical waste	Solid & Liquid	Hospital, clinic, Pharmacy Industry
4	Ink waste	Liquid	Printing
5	Wood and waste of packaging	Solid	Company Internal Activity

6	Chrome solution	Liquid	Electroplanting
7	B3 waste contaminated	Solid & Liquid	Automotive, Electronic, Chemical and Service Laboratory
8	Microbiology waste	Solid	Food and Beverages
9	Used oil waste	Liquid	Automotive, Electronic, Chemical
10	Rejected product	Solid & Liquid	Food and Beverages

Calculation of Air Emission Concentration

The output quality of the combustion process in the Incinerator is indicated by the calculation of the air emission concentration of several parameters that have been set in the regulations (GoI, 1999).

The calculation of the emission concentration is obtained by the equation used is the Bernoulli equation with the required variables being the chimney cross-sectional area, gas exit velocity and emission rate, such as the following equation:

$$C_{emisi} = A \times V \times Q$$

where:
C = Emission concentration in the chimney, mg/Nm^3
A = Chimney cross-sectional area, m^2
V = Gas velocity, m/s
Q = Emission rate, µg/second

Technical specifications of the Incinerator used can be seen in Table 3.

Table 3. Specifications of incinerator.

Parameter	Unit	Specification
Operation Time	Hour	24
Capacity	Ton/day	50
Combustion Room 1	^{0}C	700 - 1000
Combustion Room 2	^{0}C	800 - 1000
Diameter of Chimney	Meter	1.1
Height of Chimney	Meter	25
Waste Flow	Ton/hour	2,3
Retention Time of Gas	Second	2.0
Linear Gas Flow	m/sec	11.3
Flow Gas (Std, *dry basis*)	m^3/sec	4.42

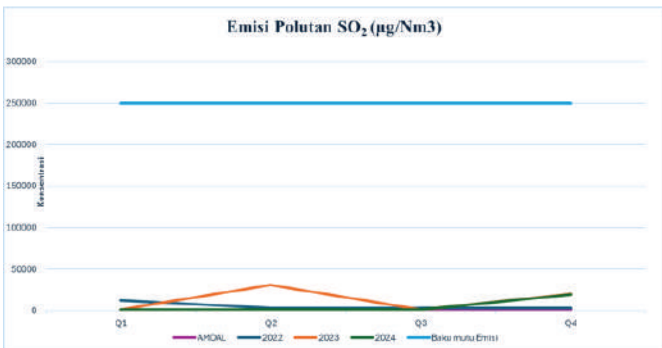

Figure 2. SO_2 Emission concentration during the period of 2022-2024.

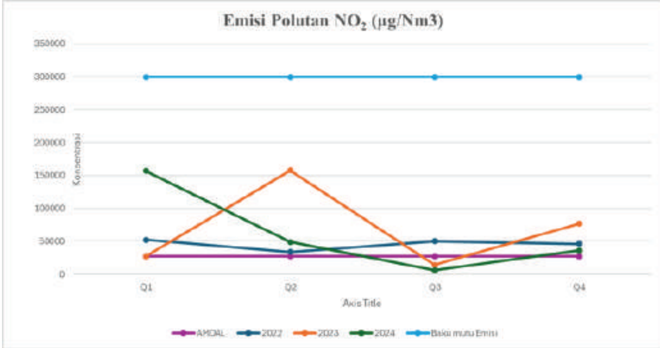

Figure 3. NO_2 Emission concentration during the period of 2022-2024.

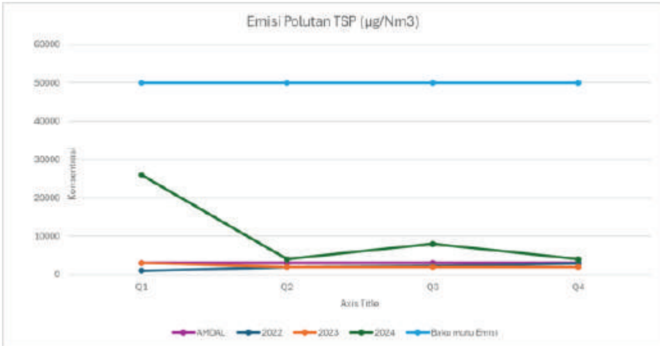

Figure 4. TSP Emission concentration during the period of 2022-2024.

From the calculation of the equation above, the data obtained for the concentration of air pollutant emissions during the research period is presented in Tabel 4.

The concentrations of SO_2, NO_2, and TSP emissions, measured in the period 2022-2024, compared with the emission quality standards are presented in Figures 2, 3, and 4.

Table 4. Concentration of pollutant emissions from incinerator chimneys.

Time	Parameter (mg/Nm^3)			AMDAL - 2018 (mg/Nm^3)			Standard (mg/Nm^3) - Pertek		
	SO_2	NO_2	TSP	SO_2	NO_2	TSP	SO_2	NO_2	TSP
Q1 - 2022	12.0	52.0	1.0						
Q2 - 2022	3.0	34.0	2.0						
Q3 - 2022	3.0	50.0	2.3						
Q4 - 2022	3.0	46.0	2.9						
Q1 - 2023	1.0	27.0	3.0						
Q2 - 2023	3.0	158.0	2.0	1.0	27.0	3.0	250.0	300.0	50.0
Q3 - 2023	1.0	14.0	2.0						
Q4 - 2023	20.0	77.0	2.0						
Q1 - 2024	1.0	157.0	26.0						
Q2 - 2024	1.0	49.0	4.0						
Q3 - 2024	1.0	6.0	8.0						
Q4 - 2024	19.0	36.0	4.0						

Calculation of Ambient Air Concentration

Pollutants emitted through the chimney will be dispersed into the air around the activity and there is the potential to pollute the air around the activity in certain areas where there are settlements. For this reason, ambient air concentration measurements are needed to determine the impacts caused along with mitigation plans. In addition, it will also be compared with ambient air concentration data obtained during the preparation of the AMDAL document. The result of measurements that have been carried out during the research period can be seen in Table 5.

Table 5. Ambient concentration of incinerator chimney pollutants during the period of 2022-2024.

Location		2022			2023			2024			AMDAL - 2018		
		SO_2	NO_2	TSP	SO_2	NO_2	TSP	SO_2	NO_2	TSP	SO_2	NO_2	TSP
		(μg/Nm^3)											
Q1	AAM-1	14	12	30	30	29	95	46	12	74	8	64	52
	AAM-2	10	12	5	30	31	82	46	12	28	9	105	30
	AAM-3	11	12	42	33	37	100	44	12	104	9	153	87
	AAM-4	13	12	9	30	21	89	46	12	82	17	167	225
	AAM-5	15	12	5	30	33	85	44	12	51	18	59	55
Q2	AAM-1	30	31	81	30	27	95	44	12	19			
	AAM-2	30	30	70	30	31	89	40	12	16			
	AAM-3	31	35	90	32	36	98	46	12	60			
	AAM-4	30	32	89	30	32	82	36	12	18			
	AAM-5	30	33	85	30	32	85	48	12	22			
Q3	AAM-1	42	41	138	34	21	95	10	12	60			
	AAM-2	31	34	70	30	35	82	4	12	81			
	AAM-3	35	39	71	39	38	92	4	12	109			
	AAM-4	30	30	83	37	35	79	6	12	88			
	AAM-5	30	36	79	33	40	87	4	12	94			
Q4	AAM-1	30	27	83	36	20	90	14	12	99			
	AAM-2	30	30	76	30	27	94	10	12	75			
	AAM-3	33	36	73	30	31	82	6	12	95			
	AAM-4	30	32	87	36	30	86	8	12	87			
	AAM-5	30	34	92	30	27	96	6	12	82			

The ambient concentration of SO2, NO2, and TSP, that measured from incinerator chimney pollutants during the period of 2022-2024 presented in Figures 5, 6, and 7.

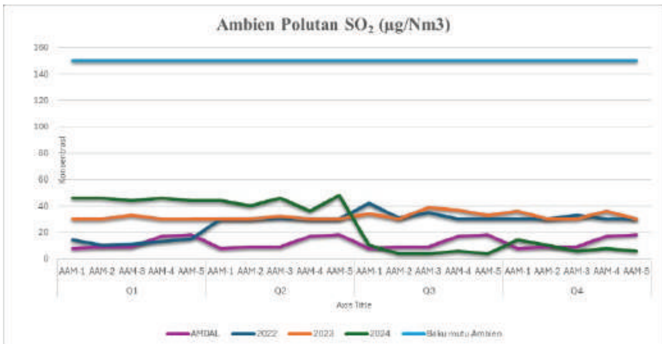

Figure 5. SO_2 ambient concentration during the period of 2022-2024.

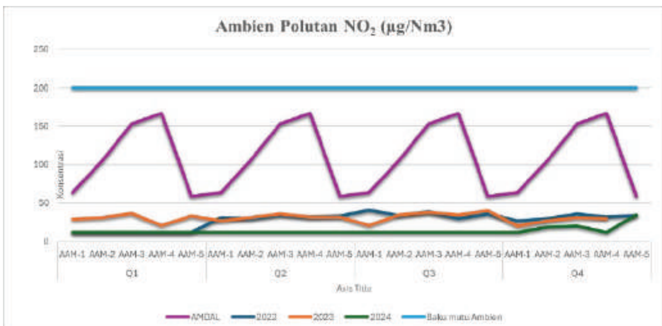

Figure 6. NO_2 ambient concentration during the period of 2022-2024.

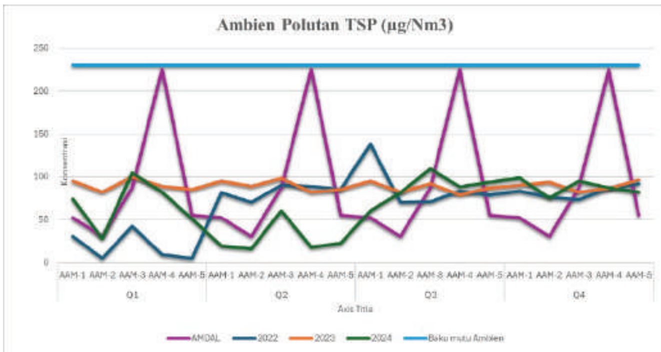

Figure 7. TSP ambient concentration during the period of 2022-2024.

Wind Speed and Direction

Wind speed and wind direction play an important role in influencing the concentration and spatial distribution of emissions released from incinerator chimneys. Based on secondary meteorological data obtained from the Meteorology, Climatology, and Geophysics Agency (BMKG) during the study period, the dominant wind direction during the rainy season (October to March) is from the southeast toward the southwest, with wind speeds ranging from 2.0 to 3.0 km h^{-1}. During the dry season (April to September), the prevailing wind direction is from the southeast toward the south, with dominant wind speeds between 2.3 and 3.7 km h^{-1}.

Dominant wind direction and speed during the period of 2022 – 2024 presented in Table 6.

Table 6. Dominant wind direction and speed in the period of 2022 – 2024.

Month	Wind direction	Average of wind speed (km/hour)	Atmosphere stability
West Monsoon (Rainy Season)			
October	Southeast	2.4	C
November	South	2.0	C
December	Southwest	2.4	C
January	Southwest	3.0	C
February	Southwest	2.6	C
March	Southwest	2.3	C
East Monsoon (Dry Season)			
April	South	3.0	B
May	South	2.4	B
June	South	2.3	B
July	Southeast	2.9	A-B
August	Southeast	2.7	A-B
September	South	3.7	A-B

Considering the dominant wind directions around the study location, the areas potentially affected by the dispersion of emissions from the incinerator chimney are located to the southwest and south of the chimney. These areas are currently characterized by bushes, quarry zones, and agricultural fields, and therefore do not directly affect residential communities at present. However, potential impacts should be anticipated if new settlements are developed in these downwind areas in the future. Wind direction and speed characteristics are effectively represented using wind rose diagrams, which provide a circular visualization of the frequency of wind occurrences from specific directions.

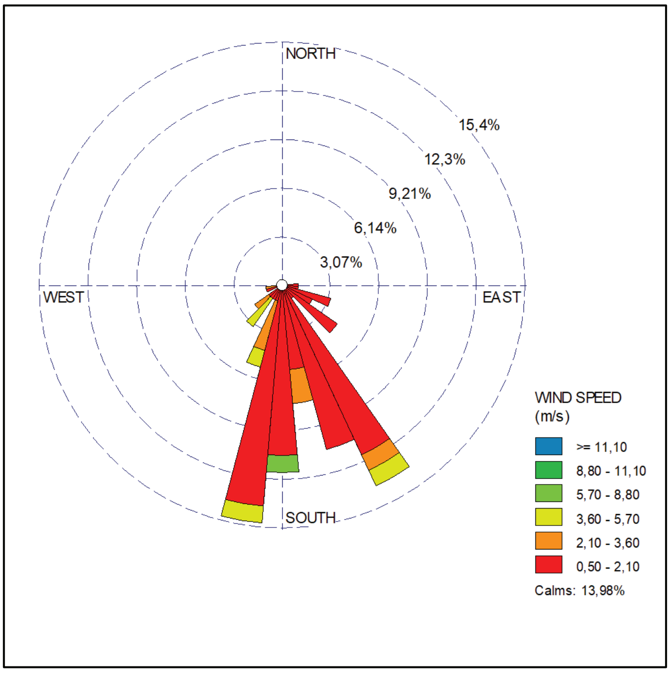

Figure 8. Diagram of dominant wind direction during rainy season.

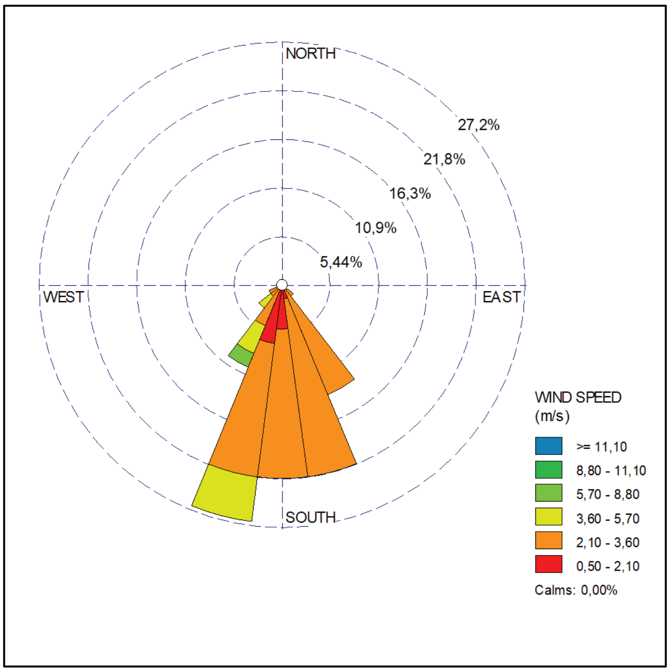

Figure 9. Diagram of dominant wind direction during dry season.

The dominant wind patterns indicate that current emissions primarily affect non-residential areas, although proactive land-use planning is needed to prevent future exposure risks to developing communities. The spread of hazardous gas pollution from industrial chimneys can be detrimental to the health of surrounding communities (Pambudi, 2023; Babagana-Kyari et al., 2024).

The dominant wind direction during the rainy season and the dominant wind direction during the dry season are shown through the wind direction diagram during the research period and can be seen in Figures 8 and 9.

Determination of Dispersion Pattern

Figures 10, 11, and 12 illustrate the distribution of SO_2, NO_2, and TSP pollutants in 2022, 2023, and 2024, respectively. These data are the result of processing data collected and test results from independent laboratories during the study. Data processing was performed using SURFER 13 software. According to Bate & Okori (2023), pollutants are negatively correlated with humidity and positively with pressure, while temperature is inversely correlated with NO_2, SO_2, and PM2.5. Pollutant concentrations are much higher during the dry season.

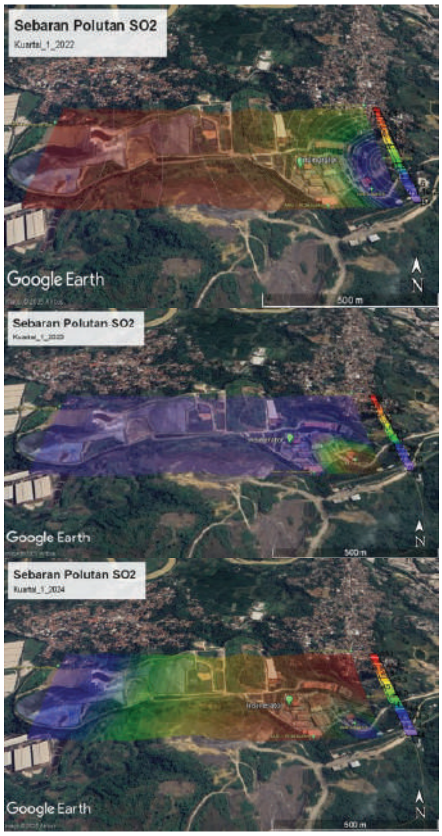

Figure 10. SO_2 pollution distribution in and around study area during the period of 2022-2024.

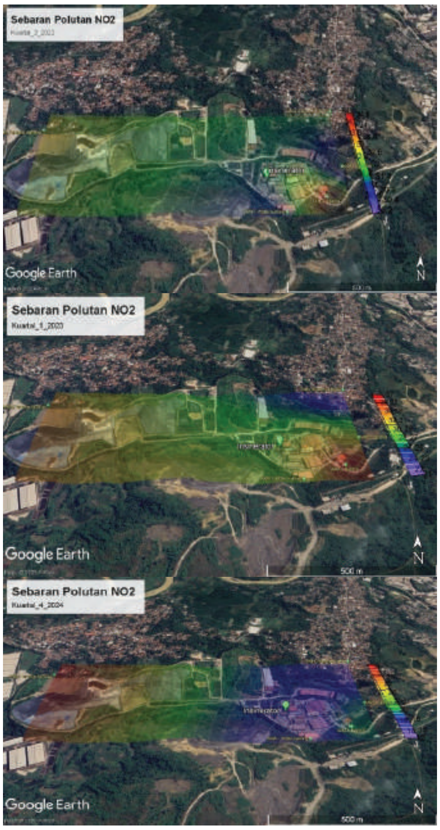

Figure 11. NO_2 pollution distribution in and around study area during the period of 2022-2024.

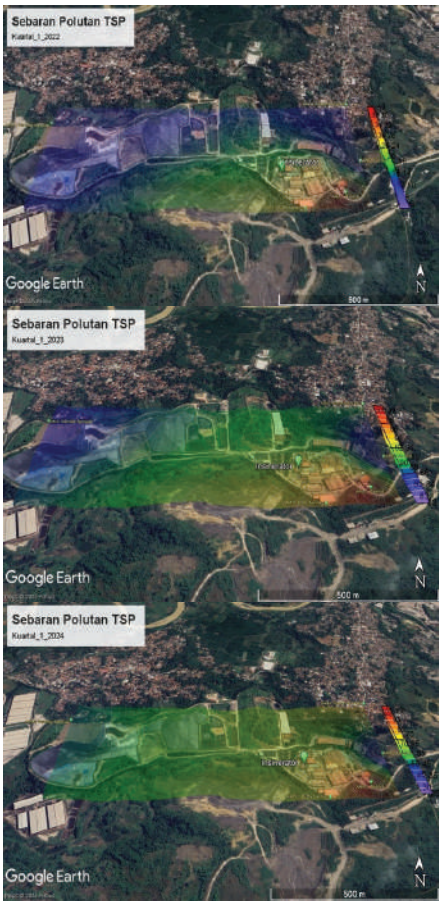

Figure 12. TSP pollution distribution in and around study area during the period of 2022-2024.

CONCLUSION

Based on the data analysis and discussion that have been conducted, several conclusions can be drawn. The distribution of air pollutants, namely SO_2, NO_2, and Total Suspended Particulate (TSP), emitted from the incinerator chimney generally moves from the southwest of the company's operational area toward the southeast and, based on the observed results, has not caused environmental pollution in the surrounding area. The concentrations of SO_2, NO_2, and TSP pollutants, both in emission sources and in ambient air, remain relatively within the predicted concentration ranges stated in the 2018 Environmental Impact Assessment (AMDAL) document, and all measured values are still below the applicable ambient air quality standards. Furthermore, the observed fluctuations in the concentrations of SO_2, NO_2, and TSP produced by the incinerator chimney, when compared to the concentration values reported in the 2018 AMDAL document, are influenced by variations in the operational activities and performance of the incinerator itself.

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